Experimental investigation on effects of liquid subcooling on droplet collision heat transfer above Leidenfrost temperature

Junseok Park[a], Hyungdae Kim[a*]
[a] *Department of Nuclear Engineering, Kyung Hee University, 1732 Deogyeong-daero, Yongin-si, Gyeonggi-do, 446-701, South Korea*
**Corresponding author: hdkims@khu.ac.kr*

1. Introduction

When a large break loss of coolant accident occurs in a pressurized water reactor, fuel rods are tremendously overheated to a temperature much higher than the Leidenfrost point. Cooling water injected by emergency core cooling systems causes several thermal-hydraulic phenomena including convection, radiation, and droplet-wall collision during the reflooding phase. Droplet-wall collision heat transfer is one of the important heat transfer mechanisms for cooling the overheated fuel rods.

Since the late 1960s, many research groups have examined the droplet-wall collision dynamics and associated heat transfer mechanisms and tried to develop its prediction model [1-4]. Recently, Lelong et al. [3] developed a prediction model for heat transfer associated with a droplet impinged on a heated surface. The total removal energy per collision was obtained by integrating conductive heat flux through the vapor layer existing between the droplet and the heated wall over a residence time, as given in Eq. (1).

$$E_d = \int_0^{t_R} \frac{k_v \pi R_S^2(t)(T_w - T_{sat})}{\delta_v} dt \qquad (1)$$

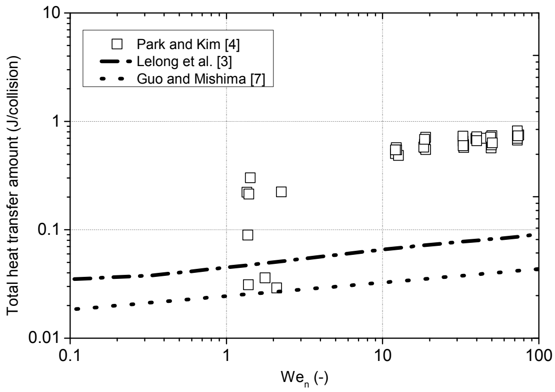

Fig. 1 Total heat transfer per a collision as a function of Weber number [4]

Very recently, Park and Kim [4] investigated the heat transfer characteristics of subcooled droplets impinged on a heated wall. It was found that there is a big deviation of experimental data from the values predicted by existing prediction correlations, as shown in Fig. 1. By carefully comparing conditions used in the correlations and experiment, it was found that droplet temperature was uncarefully treated while conducting experiments and developing prediction models. Therefore, a very plausible explanation on the observed large deviation in Fig. 1 might be related to the influence of liquid subcooling on collision heat transfer.

In this study, the droplet-wall collision heat transfer experiments above the Leidenfrost point temperature were conducted to experimentally investigate the effects of droplet subcooling

2. Methods and Results

2.1 Experiments

Dynamic behavior of a droplet impinging on the heated wall and the temperature distribution were simultaneously measured using synchronized HSV camera (Phantom v7.3) and infrared camera (FLIR SC6000, 3-5 μm) (Fig. 2(a)). To measure temperature distribution of the top surface during collision, an infrared-opaque platinum film with 100-nm thickness was deposited on the top of the sapphire disk (Fig. 2(c)). The IR and HSV cameras both recorded at a frequency of 1.7 kHz and had spatial resolutions of 87 and 37 μm, respectively.

Droplet generation system (Fig. 2(b)) consisted of a syringe pump (KSD-100), 31 gauge needle with $D_i = 130$ μm and $D_o = 260$ μm (Hamilton), supply tank and banding heater with 150 W. The droplet temperature with range from 40 to 100 °C, controlled by changing the power of banding heater, was measured using the T-type thermocouple. The collision velocity and diameter of a falling droplet by gravity were 0.7 m/s and 2 mm by analyzing high-speed images from the side while syringe needle was placed perpendicular to the test sample.

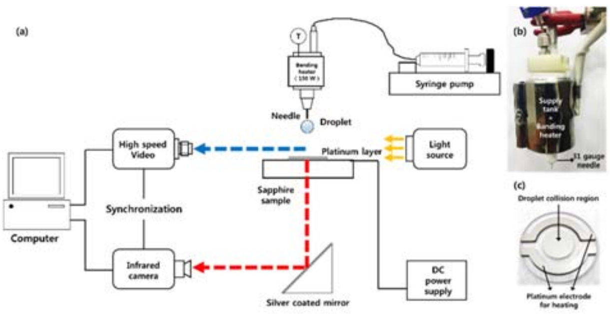

Fig. 2. Experimental setup: (a) Schematic, (b) Droplet generator, (c) sapphire sample

2.2 Data reduction

The local wall heat flux (q_w'') was directly calculated from the temperature gradient of measured with the infrared camera by solving three-dimensional transient heat conduction equation for sapphire sample. The local heat flux on the collision surface was calculated as

$$q''_w(x,y,t) = -k\frac{\partial T(x,y,z,t)}{\partial z}\bigg|_{z=H} \qquad (2)$$

Hence, the averaged vapor film thickness was calculated as follows:

$$\bar{\delta}_v(t) = \frac{k_v}{q''_w(t)}(T_w - T_{sat}) \qquad (3)$$

The total heat transfer amount for a single droplet collision (E_d) was calculated by integrating heat transfer rate with over residence time [4].

$$E_d = \int_{t_R}\int_{A_{eff}} q''_w(x,y,t)\,dA\,dt \qquad (4)$$

where A_{eff} is effective heat transfer area during droplet wall interaction was defined using the local heat flux distribution, t_R is the residence time.

2.3 Results

Fig. 3 shows histories of average vapor film thickness at each time calculated by using Eq. (3). The average vapor film thickness of saturated droplet was ranged from 40 to 120 ㎛. The vapor film thickness is decreased with the reduction of droplet temperature. The vapor film thickness of the droplet temperature with 40 °C is 9 ㎛ that is minimum value in experimental range. The calculated results showed a similar trend of the results of vapor film thickness reported by Tran [5] and Biance [6]. The vapor film thickness is thinned with the decrease of droplet temperature because the increase in the energy required for evaporation.

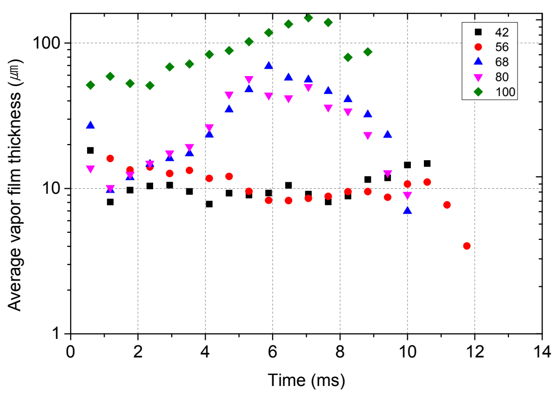

Fig. 3 Space-averaged instantaneous vapor film thickness

Fig. 4 shows a residence time of a 2-mm-diameter droplet impinging on the heated wall with 500 °C by droplet temperature ranging from 40 to 100 °C. The residence time is decreased as the droplet temperature increases. In Fig.3, the generation of vapor is reduced in according to the decrease of droplet temperature. When the droplet temperature was increased, the residence time might be decreased by the high repulsion force of the thick vapor film. In comparison between experimental results and prediction results, predicted results of Guo's model shows fairly good agreement in the experimental results of droplet with high temperature while the results of Biance's model is similar the results of droplet with low temperature. This is because the constant in Eq. (5) was determined from the experimental results using a water droplet with different temperature.

$$t_R = C\sqrt{\frac{\rho_d D_d^3}{16\sigma}} \qquad (5)$$

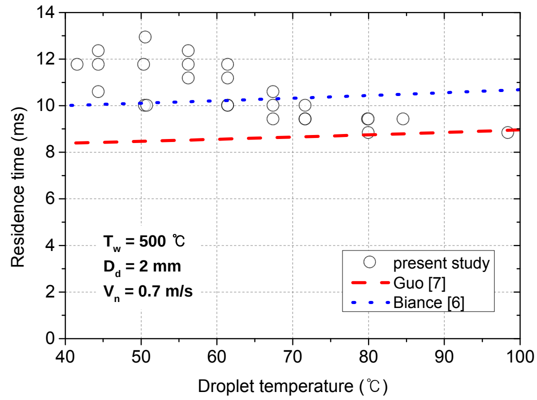

Fig. 4 Residence time according to droplet temperature

Fig. 5 shows the effective heat transfer area with time during the droplet collides with heated wall. Heat transfer area is increased during spreading process and then gradually decreased regardless of the droplet temperature. When the droplet temperature is less than 100 °C, the heat transfer area showed a similar results. For the results of 100 °C, the effective heat transfer area was smaller than the other results. This is maybe due to relatively decrement of the contact area by the thick vapor film.

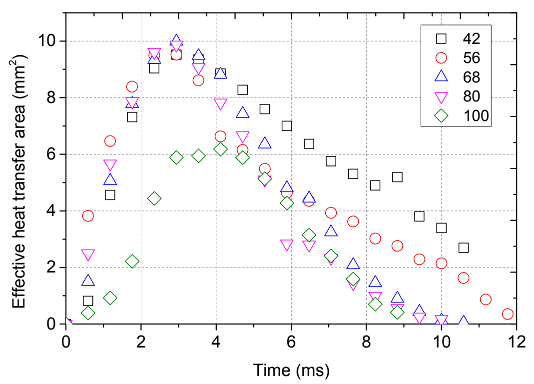

Fig. 5 Effective heat transfer area history

Fig. 6 shows an effectiveness of a 2-mm-diameter droplet impinging on the heated wall with 500 °C. Effectiveness (ε) defines the ratio of the removed energy (E_d) during a droplet-wall collision and the energy required to evaporate the droplet completely. The effectiveness tends to increase when the droplet temperature is decreased. This is caused by the decrease in the amount of formed vapor during residence time and the increase of residence time. When the droplet temperature was decreased in the experimental range, the maximum effectiveness was 10 times higher than the value of the saturated droplet. In contrast, the prediction models by Guo and Mishima [7] and Lelong et al. [3] shows opposite trends that collision heat transfer effectiveness was reduced with increasing droplet subcooling. The prediction models were developed based on an assumption that the thermal energy transferred from the wall is solely used to evaporate liquid at the interface between the vapor film and the droplet. And the models expressed the droplet subcooling effect only using the modified latent heat. Therefore, there was no chance that the additional influences of subcooling on the associated physical phenomena, such as transient conduction within a droplet.

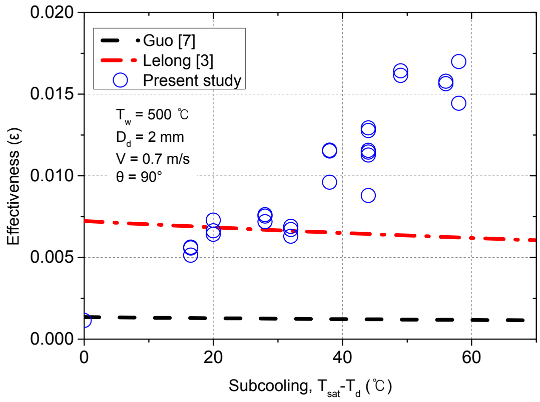

Fig. 6 Effectiveness of collision heat transfer of a single droplet as a function of subcooled temperature

To understand the effects of the droplet subcooling on the heat transfer characteristics, major parameters were measured including the vapor film thickness, heat transfer area, residence time and effectiveness. The droplet subcooling is closely related to the thickness of vapor layer in determining the heat flux of subcooled droplet. The thermal energy transferred from the solid surface across the vapor layer is balanced by the evaporation latent heat and the heat flux used to heat up the bulk liquid within a droplet. When the subcooling degree of a droplet increases, the portion of the energy for heating the droplet increases, which might yield a lower local evaporation rate. Thus, the vapor film thickness for a highly subcooled droplet is smaller compared with that for a low subcooled droplet, as shown in Fig. 3. This trend is reported through the three dimensional simulation of subcooled droplet taking into account the transient conduction [8]. Accordingly, heat partitioning considering transient conduction within a droplet is needed to develop the mechanistic model.

3. Conclusions

Heat transfer experiments during collision of a subcooled droplet with a heated surface above the Leidenfrost temperature were conducted by varying temperature of droplet from 40 to 100 °C under the conditions that the collision velocity and wall temperature were maintained constant at 0.7 m/s at 500 °C, respectively. When increasing subcooling of a liquid droplet colliding on a surface heated above Leidenfrost temperature, vapor film thickness decreases while residence time increases. Those effects significantly increase heat transfer amount beyond values predicted by existing correlations. When droplet subcooling is ~60°C, the droplet collision heat transfer effectiveness was increased by 10 times relative to the value at saturation condition of 100°C. This clearly shows that the droplet temperature affects the vapor film thickness which is one of key parameters in determining heat transfer effectiveness. Therefore, heat partitioning considering transient conduction within a droplet is needed to more accurately predict the vapor film thickness.

ACKNOWLEDGEMENT

This work was supported by the National Research Foundation of Korea (NRF) grant funded by the Korean government (MSIP : Ministry of Science, ICT and Future Planning) (No. NRF-2015M2B2A9031597).

REFERENCES

[1] S. Inada and Y. Miyasaki, "Transient heat transfer for a water drop impinging on a heated surface," Bulletin of Japan society of mechanical engineers, Vol. 28, No. 245, pp.2675 – 2681, 1985.

[2] J.C. Chen and K. K. Hsu, "Heat Transfer during Liquid Contact on Superheated Surfaces," J. Heat transfer, Vol.117, No.3, p.693-697, 1995.

[3] F. Lelong, M. Gradeck, N. Seiler, P. Ruyer, G. Castanet and P. Dunand, "Behavior of liquid droplets bouncing onto a hot slab," 23rd Annual conference on Liquid Atomization and Spray systems, Brno, Czech Republic, September, 2010.

[4] J. Park and H. Kim, "An experimental investigation on dynamics and heat transfer associated with a single droplet impinging on a hot surface above the Leidenfrost point temperature", Kerntechnik, Vol. 81, No. 3, p.233 – 243, 2016.

[5] T. Tran, H. J. J. Staat, A. Susarrey-Arce, T. C. Foertsch, A. Houselt, H. J. G. E. Gardeniers, D. Lohse, and C. Sun, "Droplet impact on superheated micro-structured surfaces," Soft Matter, 9, p.3272-3282, 2013.

[6] A. E. Biance, F. Chevy, C. Clanet, G. Lagubeau, and D. Quere, "On the elasticity of an inertial liquid shock," J. Fluid Mech., Vol.554, p.47-66, 2006.

[7] Y. Guo and K. Mishima, "A non-equilibrium mechanistic heat transfer model for post dryout dispersed flow regime," Experimental Thermal and Fluid Science, Vol. 26, p.861, 2002.

[8] Y. Ge and L.-S. Fan, "3-D modeling of the dynamics and heat transfer characteristics of subcooled droplet impact on a surface with film boiling," Int. J. Heat and Mass transfer, 49, p.4231-4249, 2006.